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A simulation study on the focal plane detector of the LAUE project

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ABSTRACT

The LAUE project, supported by the Italian Space Agency (ASI), is devoted to the development of a long focal length (even 20 m or longer) Laue lens for gamma ray astronomy between 80 and 600 keV. These lenses take advantage of Bragg diffraction to focus radiation onto a small spot drastically improving the signal to noise ratio as well as reducing the required size of the detector significantly. In this paper we present a Monte-Carlo simulation study with MEGALIB to optimize, for space applications, the detector size to achieve high detection efficiency, and to optimize the position resolution of the detector to reconstruct the Point Spread Function of the lens considered for the LAUE project. Then we will show simulations, using the SILVACO semiconductor simulation toolkit, on the optimized detector to estimate its capacitance per channel and depletion voltage. In all of the simulations, two materials were compared; a low density material (Silicon) and a high density material (Germanium).

1. Introduction

Astrophysical observations above 80 keV have been only performed by direct-viewing instruments whose sensitivity is limited by the background. Many astrophysical issues are still open at these energies [1]. For example, the origin of matter–antimatter annihilation emission at 511 keV from the Galactic Center and the accrection physics in Active Galactic Nuclei above 100 keV.

To increase the sensitivity, a new generation of broad band X-ray focusing telescopes that extend the operative energy up to several hundreds of keV is needed. The most efficient technique to focus photons above 80 keV appears to be the Bragg diffraction from bent crystals in a Laue geometry. In general, when photons of energy E impinge on crystals with grazing angle θ_B with respect to a set of atomic planes of Miller index $(h\,k\,l)$, they are diffracted according to the Bragg diffraction law:

$$2d_{hkl}\ \sin\ \theta_B = n\frac{hc}{E} \tag{1}$$

The LAUE project [2], supported by the Italian Space Agency (ASI), is a project dedicated to create a technology to construct a Laue lens with a focal length of 20 m able to focus photons in the 80–600 keV energy band. LAUE will be able to perform deep sensitive studies of astrophysical sources. It will, for example, disentangle the source physics, the emission mechanisms at work and discover new physics [3]. A Laue lens focuses gamma rays by using Bragg diffraction in the Laue geometry, i.e. in transmission. A large amount of crystal pieces are arranged in concentric rings and oriented to diffract the X-ray radiation coming from a source at infinity toward a common point (Fig. 1). Each crystal ring is symmetrical with respect to the line of sight of the lens.

Perfect single crystals are not convenient for the construction of a Laue lens given that their response covers a very narrow energy band (corresponding to the Darwin width of the crystal). Mosaic flat crystals were the first attempt to overcome the pass band requirements. In mosaic crystals, thanks to the microcrystals orientation distribution with respect to a main direction, an energy pass band corresponding to 30″–60″ is typically obtained. Bent crystals, instead, are the ideal elements to cover the entire lens surface, by obtaining a continuous (free of gaps) energy pass band.

The lens of our project has a spherical shape with radius R and focal length $f=R/2$, and makes use of bent crystals with curvature radius equal to R. In this configuration the lens becomes a real imaging focusing instrument, as will be discussed elsewhere. In the lens focus a detector is positioned, hereafter called a focal plane detector. The focal plane detector, we assume for space astronomical observations thus a space worthy instrument, is formed of several layers of Double Sided Strip Detectors (DSSDs [4]). Because they are position sensitive, these detectors are able to reconstruct the point spread function (PSF) of a Laue lens, which describes the two dimensional distribution of photons in the focal plane of the lens for a point source at infinity.

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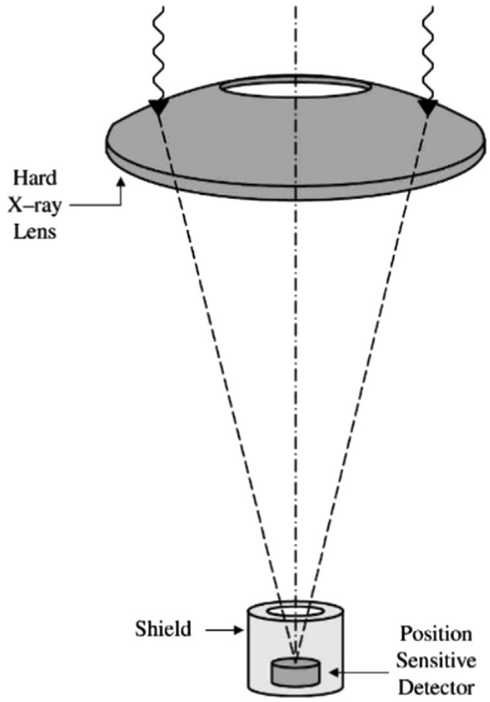

Fig. 1. Pictorial view of a Laue lens (not to scale). The lens is made of mosaic crystal tiles in transmission configuration. The impinging photons are diffracted by the crystal tiles and focused onto a small region centered in the focus of the lens where a position sensitive detector is positioned [5].

Table 1
Parameters of the lens made by GaAs (2 2 0) crystal tiles.

Parameter	Value
Energy range	80–600 keV
Focal length	20 m
No. of rings	45
Minimum radius	20.71 cm
Maximum radius	152.71 cm
Crystal material	GaAs (2 2 0)
Crystal dimension	30 mm × 10 mm × 2 mm

Using MEGALIB [6], we have performed a simulation on the focal plane detector, assumed to be 3D position sensitive. In this study two types of material were compared: a high density material (Germanium) and a low density material (Silicon). The objectives of the simulation were:

- Optimizing the volume of the focal plane detector to achieve a detection efficiency of at least 80% for the 558–645 keV photons (i.e. the photons at the upper threshold of the Lens's pass band).
- Optimizing the 2D position resolution in the focal plane in order to reconstruct the PSF under the condition that the peak intensity profile of the PSF is spread over at least 3 strips.

Hence the main goal of this paper is to optimize the coupling of the Laue lens and the detector in terms of efficiency and 2D spatial resolution. The depth resolution of the detector is not optimized in this work and typical values are assumed for each type of detector material; these will be mentioned in their corresponding sections. In addition, the detector background will be studied and taken into account in future development of the simulation work that will be presented in this paper. Despite this, we will make some considerations on the expected background for each of the considered detector material.

After optimizing the performance of the DSSDs with MEGALIB, the volume and pitch of the detectors were defined. Using the SILVACO [7] semiconductor simulation toolkit, the response of the optimized DSSDs was simulated to obtain the following information:

- The required full depletion voltage.
- The noise of the detector: capacitance and leakage current.

In the following we present the results of this study.

2. Modeling of the lens and the detector in MEGALIB

2.1. LAUE lens modeling

Bent crystals of Ge (1 1 1) and GaAs (2 2 0) with a 2 mm thickness have been selected for the LAUE project, both in transmission configuration. With a uniform thickness, the lens reflection efficency is not optimized, but this choice was imposed by current technological limitations [2]. A detailed study has been performed on these crystals in [8]. Part of this study included the simulation of an entire LAUE lens made of GaAs (2 2 0) crystals that are bent along the Laue lens radius. The lens parameters are given in Table 1. Each of the 45 rings focus photons in a defined energy band. The formula that gives the energy band focused by each ring is given by [8]:

$$\Delta E_i = f\frac{hc}{d}\frac{\Delta R}{{R_i}^2} \tag{2}$$

where ΔE_i is the energy band focused by the ith ring, f is the focal length, h is the Planck constant, c is the speed of light, R_{i} is the radius (at the center of the crystal) corresponding to the i-th ring, d is the crystal spacing (1.998 Ångstrom for GaAs) and ΔR is the length of the crystal along the Laue lens radius (in our case 3 cm). The first (i.e. innermost) ring is placed at $R=20{,}7$ cm and thus it focuses energies between 558–645 keV. The second ring is placed at $R=23.7$ cm and thus focuses energy between 492 and 558 keV and so on till the fourty-fifth and final ring which is placed at $R=152.7$ cm and focuses energy between 80 and 82 keV.

Thanks to the focusing effect along one direction of each crystal, the 30 mm × 10 mm dimension produces a diffracted image that is of the order of 1 × 10 mm. Indeed, the 10 mm dimension does not have any focusing effect but instead is extremely effective in the 30 mm direction. Given that in this paper we are not interested in the study of the lens response, we have not considered aberrations and/or distortions due to crystal misalignment errors. Hence, for the simulations, we have defined crystals directly as their image on to the focal plane (i.e. 1 × 10 mm^2 rectangles).

For our simulations, the equivalent dimension of each rectangle is that of the PSF (at 20 m from the lens) of a single crystal, whose real dimension is given in Table 1 [8]. These rectangles can then be arranged on concentric rings that have the same radius on the Laue lens as the real ones (Fig. 2). Photons with a random energy between E_{min} and E_{max} are then emitted from a random point inside each rectangle, and in the direction of the focal plane detector placed 20 m away from the ring. The overall PSF of the lens, for the 20 m focal length, is shown in Fig. 9, where the expected PSF of a lens made of GaAs (2 2 0) crystals is compared with the PSFs convolved with the detector response.

2.2. Focal plane detector modeling

The focal plane detector is modeled by assuming a rectangular prism structure placed at 20 m away from the modeled Laue lens. In reality, the focal plane detector will be formed of multiple layers